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RESEARCH MEMORANDUM

COMPARISON OF IGNITION DELAYS OF SEVERAL PROPELLANT COMBINATIONS OBTAINED WITH MODIFIED OPEN-CUP AND SMALL-SCALE ROCKET ENGINE APPARATUS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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COMPARISON OF IGNITION DELAYS OF SEVERAL PROPELLANT COMBINATIONS OBTAINED WITH MODIFIED OPEN-CUP AND SMALL-SCALE ROCKET ENGINE APPARATUS

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SUMMARY

Ignition delays of several propellant combinations obtained with a modified open-cup apparatus and with a small-scale rocket engine of approximately 50-pounds thrust were compared to study any correlations that might exist between the two methods of ignition-delay determination. The results were used in determining the relative utility of each apparatus.

The comparison showed that the results were generally similar for the same propellant combinations at the same operating conditions as long as the propellant viscosities were low enough to produce no significant effect on ignition delay. Because of this concurrence, results from the rapid-testing, open-cup apparatus can be considered sufficiently reliable in the determination of the suitability of a propellant combination with respect to ignition delay without further checking in the small-scale engine unless the propellant viscosity is a controlling factor. The small-scale engine apparatus, however, has utility in the study of the effects on ignition delay of initial ambient pressure, combustion-chamber configuration, and other factors not amenable for investigation with the open-cup apparatus.

INTRODUCTION

An important consideration in the selection of a rocket-engine propellant combination is ignition delay as influenced by parameters such as temperature, ambient pressure, and oxidant-to-fuel weight ratio. Ignition delays have been measured satisfactorily by several methods that can be grouped into three basic categories: (1) open-cup, in which one propellant is introduced into the bulk of the second propellant contained in a partially enclosed vessel; (2) impinging jet, in which streams of the two propellants meet in unenclosed space or upon some unenclosed third body; and (3) rocket engine, in which means are provided for ignition-delay measurement under practical operating conditions.

Many of these methods yield results that are reproducible insofar as each individual apparatus is concerned; however, comparisons made among various apparatus reveal that data obtained from the same propellant combinations under the same operating conditions may be very similar or widely variant.

Direct comparisons between any two particular apparatus usually cannot be made because ignition-delay investigations with the same propellants and operating conditions often do not exist. In an effort to alleviate this situation and to make an over-all appraisal of this 2793
country's ignition-delay apparatus to determine whether a standardized method of ignition-delay measurement could or should be proposed, the Naval Air Rocket Test Station submitted control propellant combinations to several laboratories with certain specified operating variables. The NACA Lewis laboratory is one of the cooperating activities; the results obtained with its two ignition-delay apparatus are presented herein.

A modified open-cup apparatus (refs. 1 and 2) and a small-scale rocket engine of approximately 50-pounds thrust (ref. 3) were used in these experiments. The control propellant combinations were hydrazine and white fuming nitric acid, hydrazine and hydrogen peroxide, and mixed butyl mercaptans and white fuming nitric acid. The tests were conducted from room temperature to the low-temperature limit of ignitibility. With the small-scale engine apparatus, additional tests were made at subatmospheric pressures and at various fuel-to-oxidant weight ratios.

A comparison of these two sets of results as well as a comparison of previously published data obtained with the modified open-cup apparatus (refs. 1 and 2) and the small-scale rocket engine (refs. 3 and 4) was made and is reported herein.

APPARATUS AND PROCEDURE

Modified Open-Cup Apparatus

The modified open-cup apparatus, shown in figure 1, consists of a test-tube reaction vessel into which a small amount of oxidant is introduced. A sealed glass ampule containing the fuel is immersed in the oxidant. The temperature of the propellants is regulated by a constant-temperature bath surrounding the test tube. The propellants are mixed when a falling weight hits a steel rod which, in turn, crushes the ampule. Simultaneously, time-measuring instruments are actuated. The end of the ignition-delay interval, indicated by the commencement of a continually persistent flame, is automatically recorded by these instruments. The apparatus is described in detail in references 1 and 2.

Small-Scale Rocket Engine Apparatus

For most of the experiments with the small-scale rocket engine apparatus, the unit (fig. 2) consisted of a transparent-sided engine of approximately 50-pounds thrust, propellant tanks, a gas-pressure-supply reservoir, a constant-temperature bath for regulating propellant temperature, a large 1500-cubic-foot altitude tank for obtaining low pressures, and a high-speed camera to record the action in the combustion chamber. When a fast-acting solenoid valve was opened, pressurized helium contained in the reservoir burst sealing disks at each end of the propellant tanks and forced the propellants from their tanks through injector nozzles and into the combustion chamber. Photographs were taken of the two propellant streams entering the combustion chamber, impinging, diffusing, and then igniting. Measurements of the ignition-delay period were made from the photographic data. The apparatus and the operating procedure are described in detail in reference 3.

For some of the runs, it was necessary to make a few changes in the apparatus and its operation. In the hydrazine - hydrogen peroxide series, modifications in the apparatus and the test preparations were made to avoid total enclosure of the hydrogen peroxide and to prevent hazardous diffusion of fuel and oxidant vapors. This was accomplished by eliminating the upper inlet disks in the propellant tanks and by installing a valve in the branch of the helium-pressure-supply line leading to the fuel tank. This valve was kept closed until a few seconds before a run was made. In this manner, the hydrogen peroxide tank was constantly vented to the atmosphere through the helium-controlled, quick-opening solenoid valve while, at the same time, intermingling of fuel and oxidant vapors was prevented.

In one run, a copper combustion chamber identical in size and shape to the conventional transparent polymeric methyl methacrylate chamber was used in an effort to contain the force of an expected explosion. For the same reason, a close-fitting 1/4-inch-thick steel cylinder with two 1- by 1-inch diametrically placed observation windows was installed over the plastic combustion chamber in several other runs.

The necessary fuel-to-oxidant weight ratios were obtained by varying the hole diameters of the propellant injectors. A propellant injection pressure of 600 pounds per square inch gage (the safe limit for the existing apparatus) was used in all the tests.

Propellants

The two control fuels and two control oxidants used in these experiments were furnished by the Naval Air Rocket Test Station. These propellants were utilized in three combinations: hydrazine - white fuming nitric acid, hydrazine - hydrogen peroxide, and mixed butyl mercaptans - white fuming nitric acid.

RESULTS

Modified Open-Cup Apparatus

A summary of the data obtained with the modified open-cup apparatus is shown in table I.

Hydrazine and white fuming nitric acid. - With hydrazine and white fuming nitric acid, two runs were made at about 68° F with a fuel-to-oxidant weight ratio F/O of 0.84. After a relatively long delay of 2793
about 58 milliseconds in each case, ignition occurred and was accompanied by a very destructive explosion (see fig. 3). Further tests with this propellant combination were then cancelled.

Hydrazine and hydrogen peroxide. - Two runs were made with hydrazine and hydrogen peroxide. At 66° F and an F/O of 0.64, a delay of 11 milliseconds was obtained. At 34° F and the same F/O, the delay decreased to 8 milliseconds. This decrease is unusual since ignition delays ordinarily, but not always, increase with decreasing temperature. Each run was accompanied by an explosion, the intensity increasing with a decrease in temperature.

Mixed butyl mercaptans and white fuming nitric acid. - Twelve runs were made with mixed butyl mercaptans and white fuming nitric acid. An F/O of 0.30 was used in each case. The ignition delay increased with a decrease in temperature, ranging from an average of about 55 milliseconds at 71° F to 110 milliseconds or infinity (no ignition) at -1° F. In four trials, no ignition was obtained at -37° F. A nondestructive explosion accompanied each ignition.

Small-Scale Rocket Engine Apparatus

A summary of the data obtained from 35 runs with the small-scale engine apparatus is shown in table II.

Hydrazine and white fuming nitric acid. - In the hydrazine - white-fuming nitric acid series, a total of 12 runs was made with one resulting in an explosion. Except for the latter, the ignition delay of all measurable runs was 5.5 ± 1.5 milliseconds. These runs were conducted at temperatures of 72° and 36° F, initial ambient pressures of 760 and 50 millimeters of mercury, and F/O from 0.5 to 1.1. For the runs at low initial ambient pressures, the average delays were slightly longer than for those at sea-level pressure. Except for the tests at an F/O of 1.1, all runs resulted in "hard starts" as indicated audibly and by the high-speed motion-picture records. The run that was terminated by an explosion (run 188) had a delay of 8.4 milliseconds. This is in accord with other small-scale engine tests which indicated that ignition delays for runs resulting in explosions are usually longer than for normal runs at the same conditions (ref. 3).

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Hydrazine and hydrogen peroxide. - In the hydrazine - hydrogen peroxide series, some preliminary experiments were made to determine the effect of hydrogen peroxide on the polymeric methyl methacrylate used in the fabrication of the combustion chamber. These experiments were deemed desirable since contact of concentrated hydrogen peroxide with most organic substances usually results in very active reactions. A laboratory test and a simulated run with only the hydrogen peroxide entering the combustion chamber (run 208) demonstrated the plastic to be inert to hydrogen peroxide at room temperature and pressure. The only result was a superficial etching of the smooth surfaces of the material.

Of nine actual runs, the first seven were terminated by explosions. In each case, the damage was not too great, being confined mainly to a shattered combustion chamber. The widely variant ignition delays ranged from 9.3 to 33.5 milliseconds and could not be correlated successfully with either temperature, initial ambient pressure, or F/O. This variance has been found to be characteristic of runs resulting in explosions (ref. 3). The test temperatures were 72° and 36° F, the initial ambient pressures were 760 and approximately 50 millimeters of mercury, and the values of F/O were between 0.5 and 0.8.

Since an "explosion" might be considered as a "hard start" with sufficient intensity to destroy the combustion chamber and to do other damage, an effort was made to prevent the destruction of the chamber by substituting a copper cylinder for the conventional plastic one. A run was made at 72° F, sea-level pressure, and an F/O of 0.65 to determine if the high initial transient pressures could be contained (run 217). Upon its success, another run was made at the same conditions to obtain photographic data (run 218). In this run, a close-fitting steel cylinder with windows was placed over the plastic chamber in an effort to contain the expected explosion. Although a hard start was obtained, the run was satisfactory and yielded a short delay of only 4 milliseconds. The conditions of the run were severe enough to create a crack in the exhaust nozzle and to reduce a portion of the plastic combustion chamber to approximately one-half of its original thickness; because of these mechanical difficulties, no additional runs were attempted.

Mixed butyl mercaptans and white fuming nitric acid. - In the mixed butyl mercaptans - white fuming nitric acid series, a total of 13 runs were made with 5 resulting in explosions. With the exception of two runs that resulted in doubtful ignitions (runs 199 and 201), the delay of all the measured runs at room temperature and pressure and at F/O from 0.2 to 0.4 was 38 ± 4 milliseconds. Each one had a hard start. All the remaining runs at reduced temperatures and pressures were terminated by explosions. The average ignition delay for runs at room temperature and 50 millimeters of mercury was 84 milliseconds. Two runs were made at -36° F and sea-level pressure. After long delays of at least 400 milliseconds, both runs resulted in destructive explosions even though one of them (run 219) utilized the steel shield over the combustion chamber. The damage created by the detonation of run 219 is shown in figure 4. This run demonstrated the usefulness of an unmodified plastic combustion chamber as a "fuse" in the apparatus. The shattering of the chamber before excessive pressures are reached acts as a relief valve and is a means for reducing the extent of damage caused by an explosion.

DISCUSSION

Comparison of Experimental Data

The results of the ignition delay experiments in the two apparatus are compared in Table III. Values of ignition delay for the two apparatus compare favorably for all combinations except two: hydrazine - white fuming nitric acid, and mixed butyl mercaptans - white fuming nitric acid at -40° F. For the latter combination, the delays obtained with both apparatus were greater than 60 milliseconds, which is outside the range of practical interest for engine starting. No explanation for the difference in the results for the hydrazine - white fuming nitric acid combination has been found.

On the basis of a delay value of 60 milliseconds as an arbitrarily selected upper limit for satisfactory ignition, the two apparatus agree in selection or rejection of fuels tested.

Comparison of Published Data

To substantiate the view that the two apparatus agree on selection or rejection of fuels on the basis of ignition delay, additional data for other propellant combinations (refs. 1 to 4) obtained with both apparatus have been compared. Since the methods of mixing the propellants in the two apparatus differ and since viscosity of the fluids influences this mixing, the data were grouped according to propellant viscosities.

The propellants with viscosities of 20 centistokes or less are shown in table IV. Agreement of actual ignition-delay values in the group of propellants with short ignition delays was very good, with 4 milliseconds being the greatest observed difference. As before, there was considerable difference in the values for ignition delays greater than 60 milliseconds; however, the two apparatus still agree on selection or rejection of fuels if a delay of about 60 milliseconds is assumed to be the upper limit for satisfactory ignition.

Only one set of comparative data is available in which a propellant viscosity exceeded 20 centistokes. It had been obtained at several temperatures below -76° F with a fuel mixture of orthotoluidine and triethylamine (3:7 by volume) and a low-freezing-point red fuming nitric acid (refs. 2 and 4). In these data, an apparent effect of viscosity on ignition delay was observed with the open-cup apparatus, but not with the small-scale engine. These relations are shown in the following table:

Temperature, °F	Approximate fuel viscosity, centistokes	Average ignition delay, millisec	
		Modified open-cup	Small-scale engine
68	1	19	15
-40	6	24	25
-76	20	38	28
-87	34	47	29
-89	40	75	29
-95	58	100	30
-103	110	167	--

Below -76° F, the open-cup ignition delays, as well as the fuel viscosities, increased rapidly with decreasing temperature. In this same region, however, there was only a slight increase in the small-scale engine ignition-delay values.

An apparent effect of viscosity on ignition delay also has been observed with the small-scale engine apparatus (ref. 4), but not until the viscosity reached about 200 centistokes.

An explanation for the effect of viscosity on the ignition delay in the two apparatus probably is that the total mixing is not as rapid nor as efficient in the open-cup as in the small-scale engine. With propellants of low viscosity, the differences in mixing rapidity and efficiency should be slight. With propellants of high viscosity, the difference in the mixing and, consequently in the ignition delay, should become appreciable.

Because of the disproportionate viscosity effects in the two apparatus, it may be concluded that results with the same propellants at the same conditions will vary when the viscosity of a propellant is above about 20 centistokes, with the degree of variation depending on the magnitude of the viscosity.

CONCLUDING REMARKS

The modified open-cup apparatus is suitable and convenient as a method for screening propellant combinations with delays in the range of interest (below 60 milliseconds) and for determining the effect of low temperature on ignition delay, provided the viscosity is not greater than about 20 centistokes. The small-scale engine apparatus is less convenient to use but is more versatile than the open-cup apparatus in that the effect on ignition delay of initial ambient pressure, combustion-chamber geometry, propellant flow rates, and oxidant-to-fuel ratios can also be determined. In addition, the apparatus is less sensitive to changes in viscosity of the propellants. 2793

SUMMARY OF RESULTS

Ignition-delay determinations of several fuels and oxidants were made at various temperatures utilizing a modified open-cup apparatus and at various temperatures and pressures using a small-scale rocket engine of approximately 50-pounds thrust. The results of these experiments are summarized as follows:

1. With hydrazine and white fuming nitric acid in the modified open-cup apparatus, the average ignition delay was 58 milliseconds at room temperature. An explosion accompanied each ignition. With the same propellant combination in the small-scale rocket engine, the ignition delay at various temperatures, initial ambient pressures, and fuel-to-oxidant weight ratios was 5.5 ± 1.5 milliseconds except for one run that was terminated by an explosion.

2. With hydrazine and hydrogen peroxide in the modified open-cup apparatus, the ignition delays were 11 and 8 milliseconds for temperatures of 66° and 34° F, respectively. Each run was terminated by an explosion. With the same fuel and oxidant in the small-scale rocket engine, the widely variant ignition delays ranged from 9 to 34 milliseconds and could not be correlated successfully with either temperature, pressure, or fuel-to-oxidant weight ratio. All these runs were made with plastic combustion chambers and were terminated by explosions. A run made with a reinforced chamber to contain the explosion yielded a short delay of 4 milliseconds.

3. With mixed butyl mercaptans and white fuming nitric acid in the modified open-cup apparatus, the ignition delays (about 55 millisec at 71° F) increased with decreasing temperature until no ignition could be obtained at -37° F. A nondestructive explosion accompanied each ignition. In the small-scale rocket engine, the ignition delay of all measured runs (except two that resulted in doubtful ignitions) at room temperature and pressure, and at various fuel-to-oxidant weight ratios was 38 ± 4 milliseconds. All runs at reduced temperatures and pressures were terminated by explosions.

4. A comparison of these and previously published data obtained with the two ignition-delay apparatus was also made and is summarized as follows:

a. With one exception, whenever ignition delays of satisfactory length were obtained in one apparatus for a propellant combination at a particular temperature, similar results were obtained in the other apparatus provided that the propellant viscosities were low enough (less than approximately 20 centistokes) to have no significant effect on ignition delay in either apparatus.

b. The one exception to the previous result was the hydrazine - white fuming nitric acid combination at room temperature. Although satisfactory delays were obtained with both apparatus, the average open-cup delay was 10 times greater than the average small-scale engine delay.

c. The effects of propellant viscosity (greater than approximately 20 centistokes) on ignition delay in the two apparatus were disproportionate with the degree of variation depending on the magnitude of the viscosity.

d. The two apparatus concurred in identifying propellant combinations with ordinarily unsatisfactory ignition properties, that is, no ignition or delays very much longer than 60 milliseconds, as long as the propellant viscosities were less than about 20 centistokes.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 18, 1953

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TABLE I. - SUMMARY OF DATA OBTAINED WITH MODIFIED

OPEN-CUP APPARATUS

Propellant temperature, °F	Fuel quantity, ml	Oxidant quantity, ml	Ignition delay, millisec	Fuel-oxidant weight ratio
Hydrazine and white fuming nitric acid				
68.9	2.0	1.6	[a]57	0.84
66.2	2.0	1.6	[a]59	.84
Hydrazine and hydrogen peroxide				
66.2	1.9	2.1	[a]11	0.64
33.8	1.9	2.1	[a]8	.64
Mixed butyl mercaptans and white fuming nitric acid				
70.7	1.4	2.6	[b]52	0.30
70.7	1.4	2.6	[b]57	.30
37.4	1.4	2.6	[b,c]63	.30
37.4	1.4	2.6	[b,c]70	.30
35.8	1.4	2.6	[b,c]85	.30
-1.3	1.4	2.6	[b,c]110	.30
-1.3	1.4	2.6	No ignition	.30
-1.3	1.4	2.6	No ignition	.30
-37.3	1.4	2.6	No ignition	.30
-37.3	1.4	2.6	No ignition	.30
-37.3	1.4	2.6	No ignition	.30
-37.3	1.4	2.6	No ignition	.30

[a]Destructive explosion accompanied ignition.
[b]Nondestructive explosion.
[c]Data from electronic counter only.

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TABLE II. - SUMMARY OF DATA OBTAINED IN SMALL-SCALE ROCKET ENGINE APPARATUS

Run	Average propellant tempera- ture, °F	Initial ambient pressure, mm Hg	Maximum combustion-chamber pressure, lb/sq in. gage	Time to attain maximum combustion-chamber pressure, sec	Temperature, °F: Fuel	Oxidant	Injector head	Constant tempera- ture bath	Nozzle plate	Ambient air	Lead propellant into combustion chamber	Time between jet entries into combustion chamber, millisec	Ignition delay, millisec	Time between ignition and explosion, millisec	Fuel-to-oxidant weight ratio
Hydrazine and white fuming nitric acid															
185	72	≈760	378	1.5	72	72	72	72	67	70	Fuel	(a)	(a)		0.80
186	72	≈760	353	1.6	72	72	75	75	69	70	Fuel	3.5	3.5		.80
209	72	≈760	347	1.2	72	72	72	75	68	71	Oxidant	.3	8.8		.80
187	36	≈760	385	1.4	36	36	36	36	60	67	(b)	<0.3	5.9	0.3	0.80
188	36	≈760	(c)	(c)	36	36	36	35	61	66	Fuel	2.0	8.4		.80
210	36	≈760	368	1.1	36	36	36	36	62	68	Oxidant	1.3	5.1		.80
190	72	49.5	377	1.2	72	72	73	73	69	72	Oxidant	1.3	6.0		0.80
192	72	50.0	378	1.1	71	72	72	72	66	71	Oxidant	1.1	6.9		.80
189	72	≈760	[d]371	[e]0.9	72	72	73	73	69	73	Oxidant	12.1	4.5		1.10
191	72	≈760	379	1.2	72	72	72	73	65	66	Oxidant	7.8	5.4		1.10
193	71	≈760	409	1.5	--	71	71	72	69	69	Fuel	2.7	4.0		.50
194	72	≈760	404	1.7	72	72	72	72	68	71	Fuel	.5	5.5		.50
Hydrazine and hydrogen peroxide															
[f]208	[f]72	≈760	(f)	(f)	(f)	72	72	72	65	71	(f)	(f)	(f)		(f)
203	72	≈760	(c)	(c)	72	72	72	72	72	74	(b)	<0.2	24.7	<0.2	0.65
[g]217	72	≈760	[d]192	[e]1.7	73	71	73	74	70	71	(g)	(g)	(g)		.65
[h]218	73	≈760	[d]208	[e]1.9	73	73	73	75	69	71	(b)	< .3	4.3		.65
205	36	≈760	(c)	(c)	36	36	—	35	65	71	Fuel	0.7	9.3	<0.3	0.65
216	36	≈760	(c)	(c)	36	36	36	36	64	69	Fuel	.5	16.5	.3	.65
207	72	49.5	(c)	(c)	72	72	72	72	70	72	Oxidant	1.3	35.5	<0.3	0.50
213	72	49.5	(c)	(c)	72	72	72	72	65	65	(b)	< .3	10.2	< .3	.65
204	72	≈760	(c)	(c)	72	72	72	72	71	74	Fuel	2.3	13.3	<0.3	0.80
206	72	≈760	(c)	(c)	72	72	72	73	69	72	Oxidant	.3	16.4	< .3	.50
Mixed butyl mercaptans and white fuming nitric acid															
195	72	≈760	290	1.3	72	72	72	72	69	72	Oxidant	0.6	35.0		0.50
196	72	≈760	315	1.2	72	72	72	73	69	73	Fuel	15.2	41.4		.50
202	-36	≈760	(c)	(c)	-36	--	-34	-36	53	55	Fuel	0.3	[i]408	0.7	0.50
[h]219	-34	≈760	(c)	(c)	-36	-36	-35	-36	56	55	Fuel	.8	[i]>575	(j)	.50
200	71	49.5	(c)	(c)	71	71	71	72	66	71	Fuel	3.4	72.5	0.6	0.30
211	72	50.0	(c)	(c)	72	72	72	72	66	66	(k)	(k)	(k)	(k)	.30
212	72	49.5	(c)	(c)	72	72	71	72	67	67	Fuel	7.4	35.5	< .3	.30
197	72	≈760	318	1.5	72	73	73	73	70	72	Oxidant	0.6	37.5		0.40
198	72	≈760	310	1.5	72	72	72	72	70	74	Oxidant	1.6	38.8		.40
199	72	≈760	(l)	(l)	72	72	72	72	68	70	Fuel	3.6	[i,m]>636		.20
201	72	≈760	(l)	(l)	72	72	72	72	70	72	Fuel	.3	[i,m]>510		.20
[n]215	72	≈760	160	1.8	72	71	73	--	72	74	(o)	(o)	(o,p)		.20
214	72	≈760	180	1.0	72	72	72	72	70	72	Oxidant	.8	34.4		.20

[a]No time records.
[b]Both propellants entered the combustion chamber in same motion-picture frame.
[c]Explosion.
[d]Peak pressure; maximum pressure possible was probably not attained.
[e]Time to attain peak combustion-chamber pressure.
[f]No fuel used. Run made to determine effect of H_2O_2 on plastic combustion chamber.
[g]Copper combustion chamber used. No film records made.
[h]Heavy cylindrical steel shield slipped over plastic combustion chamber to contain explosion.
[i]Ignition occurred after end of film roll.
[j]Explosion occurred after end of film roll.
[k]No photographic records because of defective electric system.
[l]Restriction in line from combustion chamber to pressure recorder.
[m]Doubtful ignition.
[n]Run made in complete darkness for visual check of doubtful ignitions of runs 199 and 201.
[o]No film records made.
[p]Unequivocal ignition, observed audibly and visually.

TABLE III. - COMPARISON OF RESULTS OBTAINED WITH MODIFIED OPEN-CUP AND SMALL-SCALE ROCKET ENGINE APPARATUS FOR CONTROL PROPELLANT COMBINATIONS

Fuel	Oxidant	Approximate fuel viscosity, centistokes	Approximate oxidant viscosity, centistokes	Approximate fuel-oxidant weight ratio	Approximate initial ambient pressure, mm Hg	Approximate temperature, °F	Average ignition delay, millisec	
							Open cup	Small engine
Propellant combinations with short ignition delays at indicated operating conditions (<60 millisec)								
Hydrazine	White fuming nitric acid[a]	1	1	0.80	760	70	[b]58	6
Hydrazine	Hydrogen peroxide	1	1	.65	760	70	[b]11	[b]15
Hydrazine	Hydrogen peroxide	2	1	.65	760	35	[b]8	[b]13
Mixed butyl mercaptans	White fuming nitric acid[a]	1	1	.30	760	72	[c]55	38
Propellant combination with long ignition delays at indicated operating conditions (>60 millisec)								
Mixed butyl mercaptans	White fuming nitric acid[a]	1	2	0.30	760	-37	No ignition	[b]>400

[a]Contains 2 percent water by weight.
[b]Destructive explosion occurred.
[c]Ignition accompanied by nondestructive explosion.

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TABLE IV. - COMPARISON OF PREVIOUSLY PUBLISHED RESULTS OBTAINED WITH MODIFIED OPEN-CUP AND SMALL-SCALE ROCKET ENGINE APPARATUS AT APPROXIMATELY SEA-LEVEL PRESSURE

[Propellant viscosity $\leq$ 20 centistokes]

Fuel	Oxidant	Approximate fuel viscosity, centistokes	Approximate oxidant viscosity, centistokes	Approximate temperature, °F	Average ignition delay, millisec	
					Open cup	Small engine
Propellant combinations with short ignition delays at indicated temperatures (<60 millisec)						
Mixed xylidines - triethylamine[a]	Anhydrous nitric acid	18	2	-40	34	35
Mixed xylidines - triethylamine[a]	White fuming nitric acid[b]	18	2	-40	42	[c]42
Diallylaniline - triethylamine[a]	Anhydrous nitric acid	6	2	-40	17	13
Diallylaniline - triethylamine[a]	White fuming nitric acid[b]	6	2	-40	20	17
Diallylaniline - triethylamine[a]	Red fuming nitric acid[d]	6	6	-40	28	30
Orthotoluidine - triethylamine[a]	Red fuming nitric acid[e]	20	6	-40	27	25
Orthotoluidine - triethylamine[f]	Red fuming nitric acid[e]	1	1	68	19	15
Orthotoluidine - triethylamine[f]	Red fuming nitric acid[e]	6	6	-40	24	25
Propellant combinations with long ignition delays at indicated temperatures (>60 millisec)						
Mixed xylidines - triethylamine[a]	White fuming nitric acid[g]	18	3	-40	114	[c]423
Hydrazine hydrate	White fuming nitric acid[b]	20	2	-40	No ignition	131

[a]Blend of 1:1 by volume.
[b]Contains 2 percent water by weight.
[c]Destructive explosion occurred.
[d]Contains 3.5 percent water and 16 percent nitrogen dioxide by weight.
[e]Contains 3 percent water and 19 percent nitrogen dioxide by weight.
[f]Blend of 3:7 by volume.
[g]Contains 7 percent water by weight.

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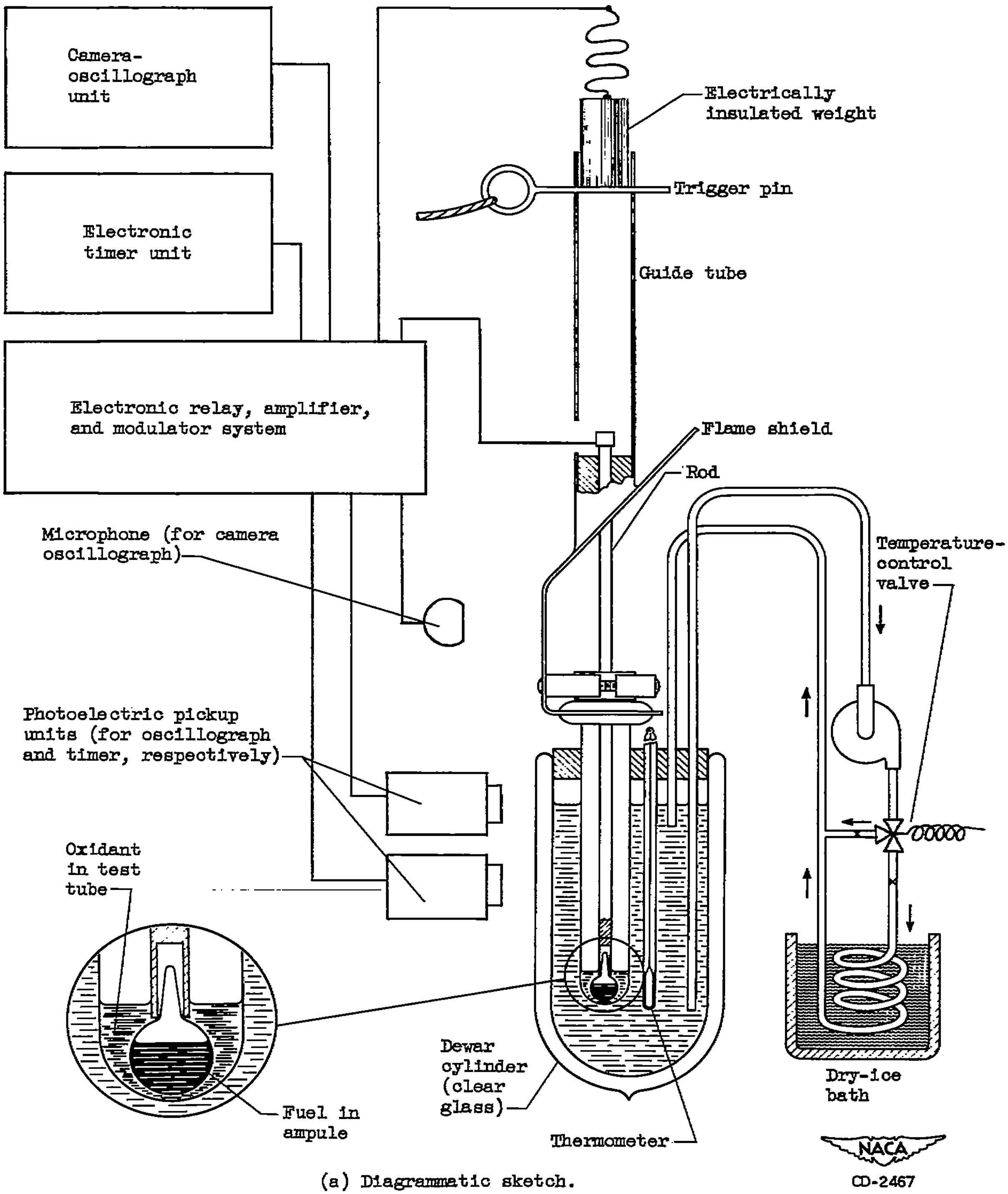

(a) Diagrammatic sketch.

Figure 1. - Modified open-cup ignition-delay apparatus.

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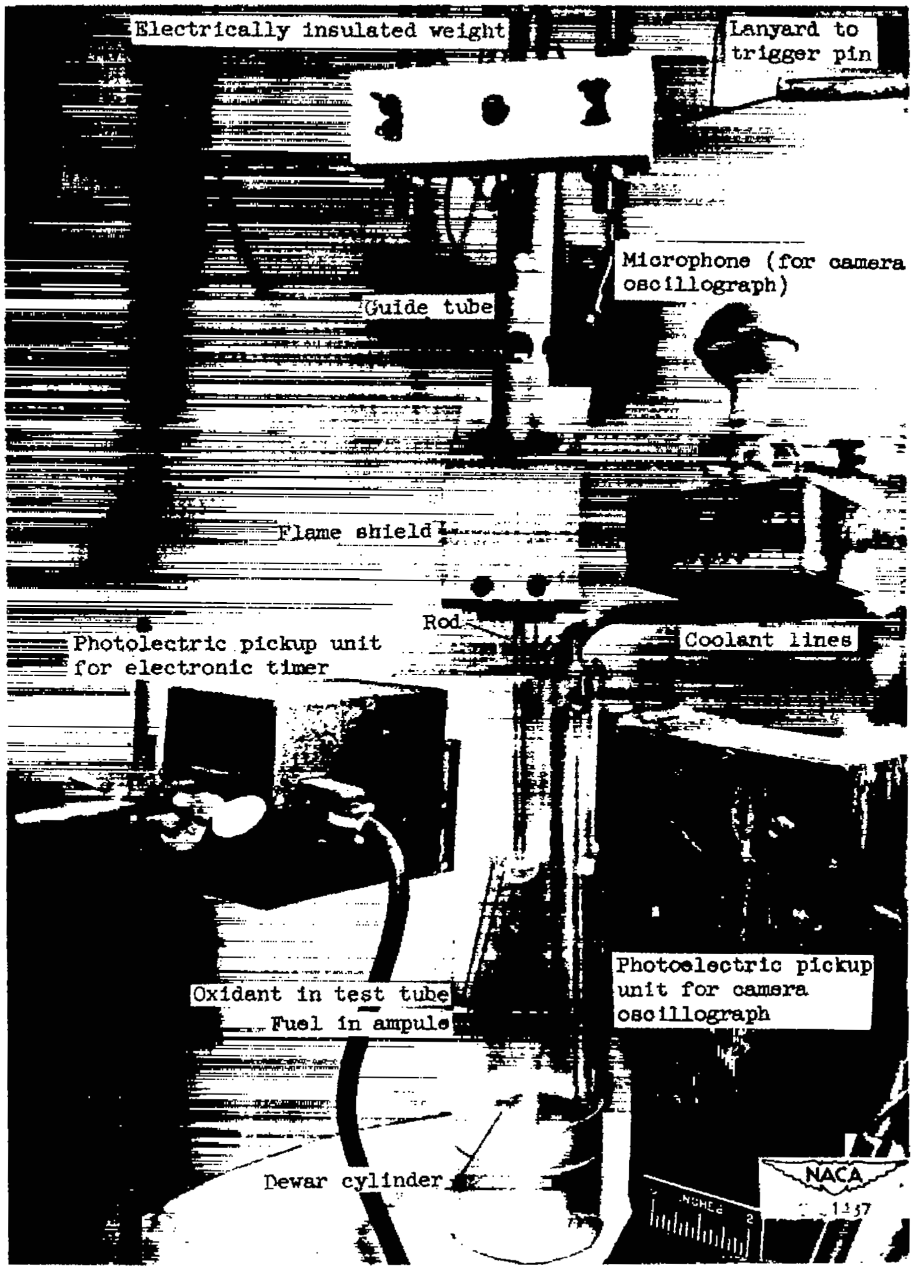
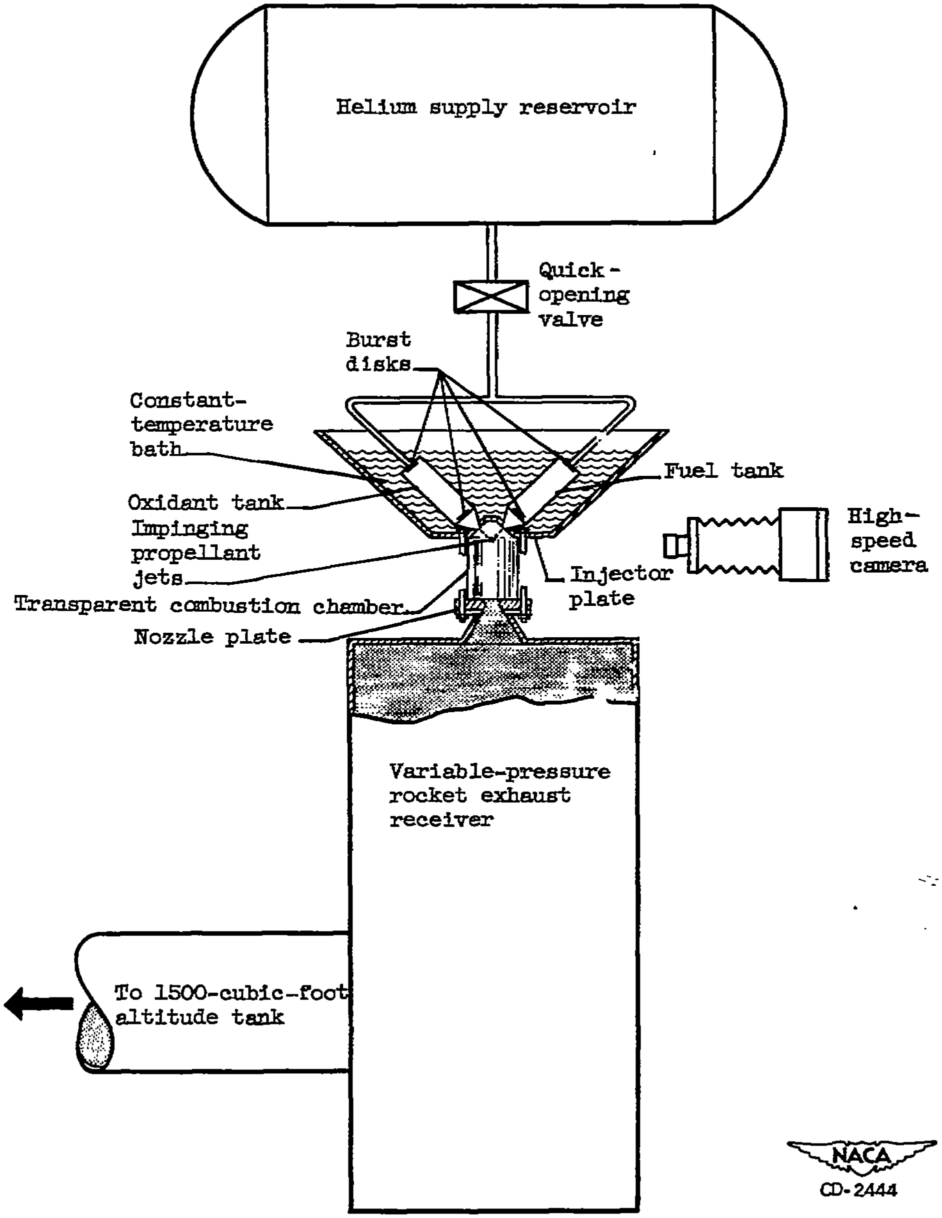


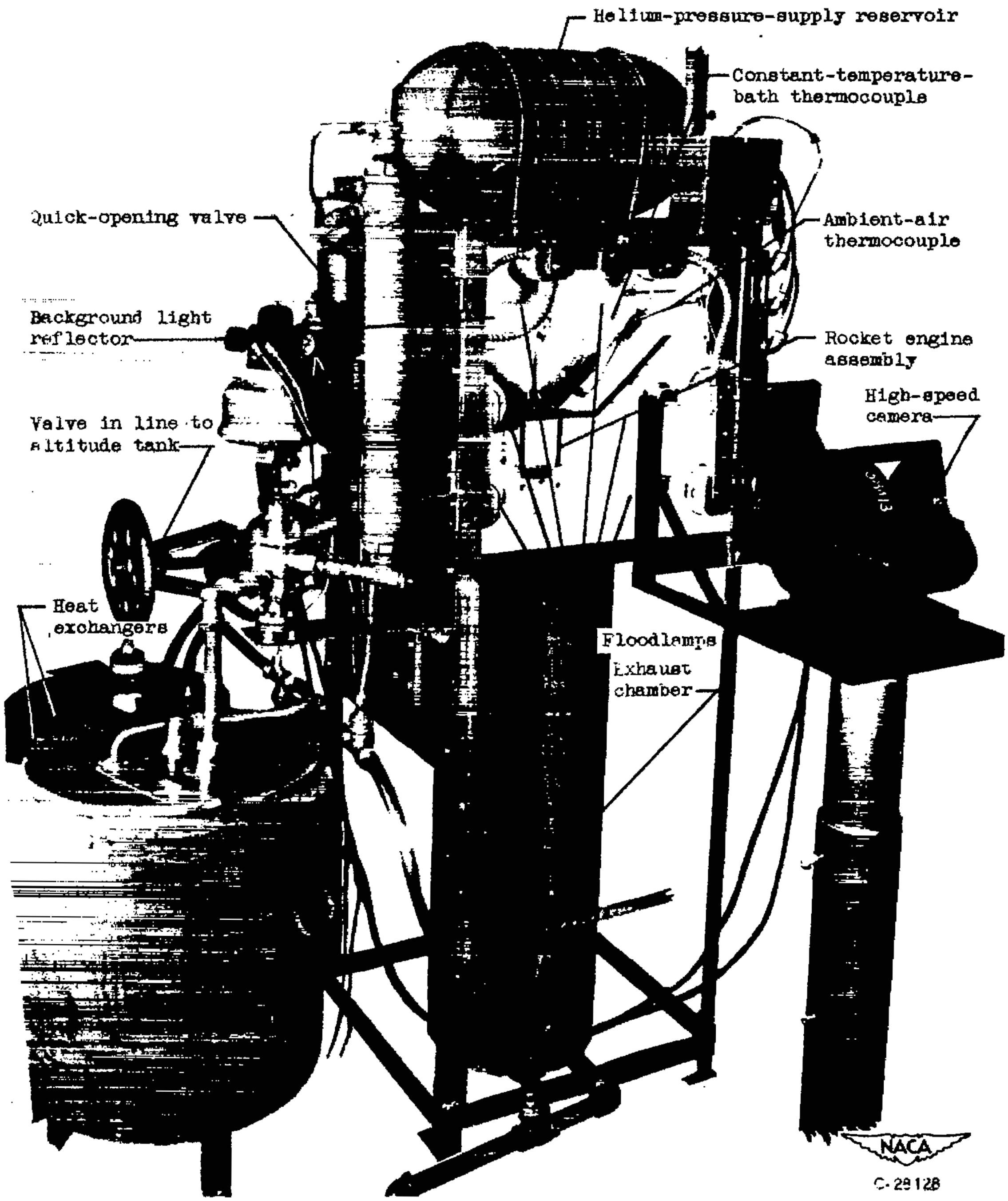
(b) Photograph of assembly.

Figure 1. - Concluded. Modified open-cup ignition-delay apparatus.



(a) Diagrammatic sketch.

Figure 2. - Small-scale rocket engine ignition-delay apparatus.



(b) Photograph of assembly.

Figure 2. - Concluded. Small-scale rocket engine ignition-delay apparatus.

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Figure 3. - Results of explosion accompanying ignition of hydrazine and white fuming nitric acid in modified open-cup apparatus.

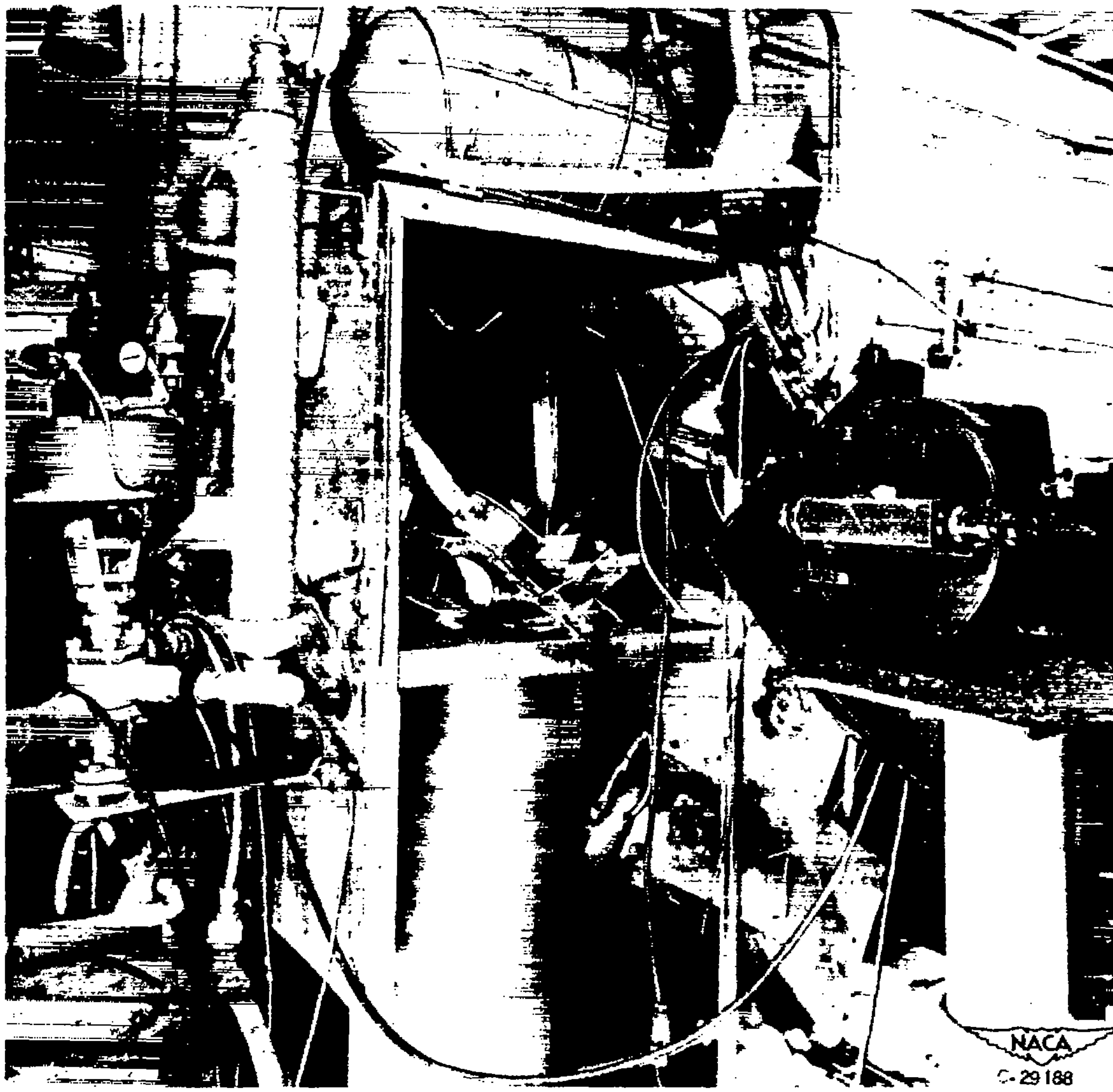

Figure 4. - Small-scale rocket engine apparatus after explosion of mixed butyl mercaptans and white fuming nitric acid at -36° F and sea-level pressure (run 219).

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